

NUCLEAR EFFECTS IN CHARM PRODUCTION[†]

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ABSTRACT

I briefly review our understanding of the nuclear target dependence of charm and charmonium production, in view of charm physics at Elfe.

Charm as a probe of hard interactions

The charm quark mass $m_c \simeq 1.5 \text{ GeV} = (\frac{1}{7} \text{ fm})^{-1}$ is large compared to the QCD confinement scale of $\Lambda_{QCD} \simeq .2 \text{ GeV} = 1 \text{ fm}^{-1}$. Hence charm physics is ‘hard’ physics, as evidenced already by the very narrow total width (86 keV) of the J/ψ . On the other hand, since the charm mass scale exceeds Λ_{QCD} by less than an order of magnitude, higher order (in α_s) and higher twist (in $1/m_c^2$) corrections can be expected to be sizable. From the point of view of precise predictions (*e.g.*, of the total charm cross section) that is a disadvantage. On the other hand, it also implies sizable signals for new physics beyond the leading twist approximation. By concentrating on relative rates (such as the dependence on the atomic number A of a nuclear target), much of the uncertainty in the absolute prediction is eliminated. Moreover, Nature has been kind enough to supply us with another readily available heavy quark, the b quark with mass $m_b \simeq 5 \text{ GeV} = (\frac{1}{25} \text{ fm})^{-1}$. Since QCD processes are flavor blind, the quark mass dependence of observables reveals whether we are dealing with a leading or a higher twist process.

From an observational point of view charm has an important advantage compared to other hard probes such as large p_\perp jets. Jets cannot in practice be detected below $p_\perp \simeq 5 \text{ GeV}$, since their transverse momentum is distributed over many soft pions. On the contrary, there is no ambiguity in measuring the momentum of D , D^* or Λ_c hadrons. The added bonus of being able to study charmonium states (J/ψ , ψ' , χ_c, \dots) has no counterpart in jet physics, and has turned out to be extraordinarily interesting. The standard QCD factorization theorem for hard processes [1] is not applicable in a situation where the heavy quarks are constrained

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to have low relative momenta, being replaced by a more sophisticated expansion in powers of their relative velocity [2]. The tentative models of charmonium production (Color Evaporation, Color Singlet, Color Octet,...) are in fact having a hard time describing the data [3].

A prime purpose of physics at Elfe will be to investigate the space-time dynamics of hard collisions. Through the use of nuclear targets, additional information about the short time development of the scattering process can be obtained. The moderate hardness scale offered by the charm quark implies that charm physics will be an important part of this endeavour. In the following I shall touch upon some of the topical questions of charm physics which are related to nuclear target dependence.

Nuclear target dependence

At leading twist, charm production proceeds via subprocesses such as $\gamma^*g \rightarrow c\bar{c}$ in lepton production, and $gg \rightarrow c\bar{c}$ in hadron collisions. The measured total charm cross section is found to be in rough agreement with QCD expectations, within the rather large uncertainties due to scale dependence and higher order perturbative corrections [3, 4].

The hadroproduction of D mesons on nuclear targets has been well measured in proton collisions at 800 GeV. Parametrizing the A -dependence as $\sigma(pA \rightarrow D + X) \propto A^\alpha$, E769 [5] finds an average $\alpha = 1.00 \pm .05 \pm .02$ for $0 < x_F(D) < 0.8$. The E789 Collaboration [6] similarly obtains $\alpha = 1.02 \pm .03 \pm .02$, for an average $\langle x_F \rangle = 0.031$. Thus charm production (in the region of small x_F which dominates the total cross section) is consistent with the leading twist expectation of being additive on all partons in the nucleus. This is to be compared to the typical values $\alpha = 0.7 \dots 0.8$ found for light hadrons (π , K , $p \dots$) in this kinematic region [7]. Clearly charm production qualifies as a hard process.

The A -dependence of inclusive charmonium (J/ψ , ψ') and bottomonium production [8] reveals that the reaction dynamics is considerably more complicated than for open charm.

(a) $.1 \lesssim x_F \lesssim .3$

The effective power is $\alpha \simeq .92 \pm .01$ in this region [8]. The value of α for inclusive J/ψ and ψ' production is found to be the same within errors. This is expected since at the high beam energies involved the $c\bar{c}$ pair remains compact ($r_\perp \simeq 1/m_c \ll r_{J/\psi}$) inside the nucleus, with charmonium formation occurring long after the pair has left the nucleus.

The A -dependence for Υ production is characterized by $\alpha \simeq .97$. Since this is much closer to unity than in the case of charmonium, the deviation of α from 1 is apparently due to a higher twist effect. For the Drell-Yan process of lepton pair production $\alpha \simeq 1$ [9], as it is for

open charm (D) production [5, 6]. This suggests that (elastic) scattering of the heavy quarks in the nucleus, which can increase their relative momentum, may be a reason for the nuclear suppression. There is no such scattering for leptons, and it is irrelevant for open heavy quark production. The more compact the pair is (*i.e.*, the heavier the quark mass,) the harder must the secondary elastic scattering be to resolve the pair. This would explain the higher twist nature of the effect.

(b) $x_F \gtrsim .4$

In this region, α is found to decrease with x_F , with $\alpha(x_F \simeq .6) \simeq .8$ [8]. Such x_F dependence is inconsistent with QCD factorization of the cross section into a product of the hard subprocess and beam and target structure functions [10]. Since factorization should hold at the leading twist level [1], this indicates that there are important higher twist effects also in this region of x_F . The suppression of Υ production is again found to be appreciably less than for the J/ψ , which is consistent with this conclusion.

An early suggestion for the x_F -dependent suppression of charmonium production was energy loss due to gluon radiation from secondary interactions in the nucleus [11]. There is, however, a general limit to such radiation set by the uncertainty principle [12]. Only gluons whose formation time are commensurate with the nuclear radius R_A can be emitted inside the nucleus. This imposes a limit on the momentum carried by such gluons, $x_g \lesssim \langle p_\perp^2 \rangle > R_A/2E$. At beam energies E of several hundred GeV this implies negligible energy loss, if one assumes an average hardness $\langle p_\perp^2 \rangle \simeq 0.1 \text{ GeV}^2$ for the secondary scattering in the nucleus. It has recently been proposed [13] that the secondary nuclear scattering could be much harder, which if true would be very interesting.

Alternatively, the suppression in the large x_F region may be due to scattering not from the heavy quarks, but from the low x ‘stopped’ light quarks which transferred their momentum to the heavy pair [14]. In the limit where $m_c^2 \propto 1/(1 - x_F)$, the light quarks are coherent with the heavy pair. Hence scattering from the light quarks can put the heavy quarks on their mass shell. The scattering cross section from the light quarks is large, implying a dominance of surface scattering on the nuclear target, *i.e.*, $\alpha \simeq 2/3$. A mechanism of this type seems in any case to be required to explain why the J/ψ becomes longitudinally polarized in πN interactions as $x_F \rightarrow 1$ [15]. It is likely that this is due to helicity conservation from the pion projectile to the leading J/ψ , which requires the full pion Fock state to interact coherently [16].

In inelastic J/ψ photoproduction the nuclear target dependence has been measured as $\alpha = .99 \pm .04$ (for $p_\perp^2 > 1 \text{ GeV}^2$) by E691 [17], and as $\alpha = 1.05 \pm .03$ (for $x_F \leq 0.85$, $p_\perp^2 > 0.4 \text{ GeV}^2$)

by NMC [18]. The photoproduced J/ψ 's are dominantly produced at large x_F . The absence of a nuclear suppression may be partly due to the cut in p_\perp , which tends to enhance nuclear rescattering. Another reason may be the simpler Fock state structure of the photon, compared to hadrons (*c.f.* the remarks above on coherent scattering of hadron projectiles).

(c) $x_F \lesssim 0$

The value of α measured in $pA \rightarrow J/\psi + X$ is found to decrease also as one approaches the nuclear fragmentation region [8]. The suppression observed for Υ production is similar to that for charmonium. A tentative explanation for this is comover interactions – partons moving with similar velocities as the heavy quarks interact strongly with them, and may suppress quarkonium formation [19]. Since there are more comovers in the fragmentation region of heavy nuclei, the comover effect should increase with A .

At a proton beam energy of 800 GeV a J/ψ with $x_F \simeq 0$ has an energy of about 60 GeV in the nuclear rest frame. The energy E_{com} of a light comover of similar velocity is reduced by a factor $\langle p_\perp \rangle / M_{J/\psi}$, thus $E_{com} \simeq 6$ GeV. Such a comover would be a ‘wee’ parton in the nuclear wave function. A better understanding of the comover effects may be provided by experiments where a heavy ion beam is scattered on a hydrogen target, so that the nuclear fragmentation region is experimentally more accessible.

It should be clear already from the above brief review (from which several other outstanding puzzles of quarkonium physics were omitted due to the constraints of space) that charmonium production is a rich field of study, and that nuclear targets can give us valuable information on the scattering dynamics. At Elfe energies, one will be able to study the effects of charmonium formation inside the nucleus. The experimental observation of charmonia with low laboratory energies is thus an important challenge.

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